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Algorithm to Calculate Heart Rate and Comparison of Butterworth IIR and Savitzky-Golay FIR Filter

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Abstract

Heart Rate is an important physiological parameter for health monitoring. Heart Rate measurement with smart phone is used by many people all over the world and different applications are developed. But, there are few issues behind the proper measurement like motion, baseline drift, power line interference, low amplitude PPG, and premature ventricular contraction and noise in the signal. While capturing red contact video of fingertips, miss touch errors can produce significant variation in real result as noise gets incorporated. Similarly, high pressure on camera and low pressure on camera can produce incorrect PPG signal and therefore, mislead to incorrect result. They can be treated as noise and needs to be removed up to a level to keep up the originality of a signal to give correct BPM rate. Here, in our study we have introduced an algorithm to get rid of certain percent of miss touch errors and thereby calculate heart rate from noise free signal, accurately. Here in our study, we have focused on Non-Invasive PPG signal based Heart Rate monitoring from skin blood flow using IR light at 900 nm wavelength. We have captured contact unfocused video to capture PPG using smart phone and developed algorithm to remove some percent of touch errors and followed by noise removal with 2nd Order Butterworth (IIR) band pass filter with frequency domain analysis and Hann Windowing for leakage reduction. We have also completed a comparative study in between Butterworth filter and Savitzky-Golay filter. The PPG is obtained from RED channel of the captured live video of smart phone camera.

Keywords: ECG; PPG; Sampling; Filter design; FFT; Filter; Pixel density; Smoothening

Introduction

Cardiovascular problem is one of the major concerns in these days as majority of the people die from this problem annually. In 2015, it was responsible for 31% of the total death and estimated around 17.7 million people. The number is increasing alarmingly and sources claimed that total estimated global cost of cardiovascular disease was $863 billion in 2010 and it might likely to increase by 2030 to $1044 billion. Here in our study, we have focused on PPG signal that is measured from skin blood flow using IR light. First target is to obtain smooth leakage noise free PPG signal from Video on RED plane and thereby peak counting from normalized signal and resultant value is multiplied by 60 (1 minute) to calculate the heart rate which is an important parameter for cardiovascular monitoring, health coaching etc. It is non-invasive, inexpensive, portable and convenient diagnostic tool. Analyzing PPG, we can calculate Oxygen saturation (SPO$_2$), blood pressure (systole/diastole), Heart Rate, Arterial age, vascular disease, HB Count, RBC count prediction, circulatory and respiration monitoring etc.

While capturing red contact video of fingertips, miss touch errors can produce significant variation in real result as noise gets incorporated. Similarly, high pressure on camera and low pressure on camera can produce incorrect PPG signal and therefore, mislead to incorrect result. They can be treated as noise and needs to be removed up to a level to keep up the originality of a signal to give correct BPM rate. Here, in our study we have introduced an algorithm to get rid of certain percent of miss touch errors and We have focused on smoothening Savitzky-Golay filter instead of Butterworth filter, if can be used with inspiration from one referenced paper and has performed a comparative study for algorithm improvement.

PPG

Mobile camera detects Electro Magnetic radiation at 350-1000 nm wavelengths and in that wavelength range; 700-1000 nm is IR radiation.

Infrared is a special form of invisible electromagnetic wave that can be felt by heat. Visible light's wavelength is 400-700 nm [1-5]. For better picture, IR radiation is blocked by film or so called filter. If no IR filters in the camera, pictures will not be as good as digital camera. For capturing fingertip video, we must ensure that the touch is proper and to check if fingertip is properly placed on camera or not:

- Touch Camera → Capture Video of RED image

- Check Red Image Frame → Average Pixel density

Average pixel count/frame, if>200: 'Placed Properly'. Else 'not placed properly'.

If more contact pressure excreted on camera:

- Deforming arterial wall leads to wrong reading.

- Block micro circulation in the capillary.

- Pixel density / frame in Red plane<200 if pressure on a single area and in case of uniform more pressure than pixel density/frame in Red plane>200 but sudden up and down of pixel density.

- After FFT analysis of brightness signal flat line (Y=constant) is produced.

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• Results reduced correct frame count for brightness calculation.

FPS or flips per second or frame rate is a property of digital camera to capture video of an object. Experiment has shown that human eye can differentiate images at 16 fps but exact human perception is still a research area and depends on human to human [6-10]. Standard FPS rate is considered to be 30 fps to have a clear smooth video. In our mobile, the general FPS range is 25-30 and we have used same value as sampling frequency for filter design and other calculation (Figure 1).

PPG is used to determine variation in blood flow/volume in the body which occur with each heartbeat. It reflects the blood movement in the vessels that travels from heart to fingertips and toes through the vessels in the wave like motion and it is measured optically with the help of light intensity (as amplitude of the signal over time). From light source/camera, light is sent to the tissue and part of it is absorbed (DC part/Fixed Absorbance) and some part is backscattered which corresponds to variation of blood volume (AC part/Modulated Absorbance). This light is invisible and falls in the wavelength range of IR. Its intensity variation graph gives us the heart beat graph over time. Systole means more pressure is delivered by heart to pump out blood and more blood on fingertip vessels and less reflective index and more light absorption. It gives frames with darker intensities and vice versa for diastole [10-12] (Figures 2 and 3).

The process can be summarized as: Cardiac cycle → blood volume change in tissue → Ambient Light → Illuminates skin →Light goes to the tissue → RED image frame → Calculates light intensity of the frame → Receive data → Signal → FFT (Sampling rate and window) → Heart Rate Calculation.

Assumption

For age/condition/physical activity: 60-200 bpm is in general. Here, Experimental purpose: 40-220 bpm=667 to 3.66 Hz. Sampling Frequency=2* 3.66 Hz=7.32 Hz (Nyquist)<8 Hz. NB: DC component operates at 0 Hz and low frequency noise up to 0.5 Hz so filtering at above range will help PPG to get rid of DC and low frequency noise.

Conventional PPG Algorithms

Appropriate selection of sampling rate and the number of FFT points result in good performance in real time HR calculation. We have studied few available algorithms but found some issues with them while trying to replicate in real life scenario with raw captured video [13,14].

• Multiple operation on signal like Filtering, FFT, windowing, Smoothening are not producing correct result and originality of the signal is lost.
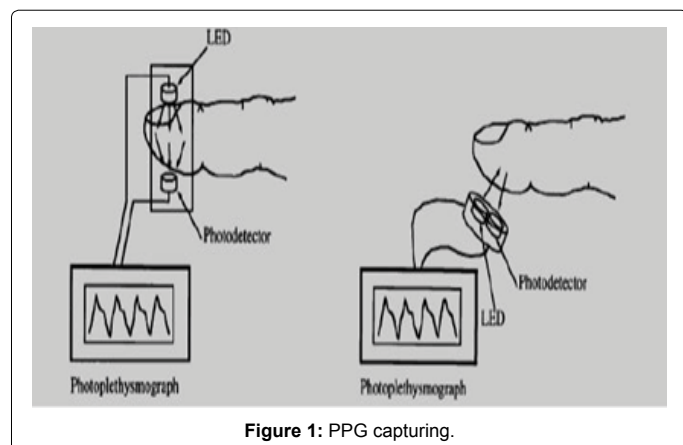
• Mistouch errors are not considered.

• Pixel density is not analyzed for high fingertip pressure on camera.

• Few algorithms have considered fixed number of frames instead of all.

• Default sampling frequency/fixed frequency resolution is considered, but for PPG capturing from live video and HR calculation depends on fps. It is directly proportional to HR while other conditions are unchanged.

• Sometimes, No Noise filtering and only noise free signal has been considered

• No Leakage coverage or filter stabilization is considered.

Proposed Algorithm

We have proposed one algorithm in this paper with below features:

· Sampling frequency is not fixed and it is round (fps) of captured video so no hard coding or manipulation.

· Calculated Average Pixel density/frame on red plane and if it is touched properly then value is considered else rejected   Touch error elimination.

· We have used FFT point as 128 and 2nd Order butter worth band pass filter can be used for removing low frequency and high frequency outliner noise.

· For filtering pass band is 40 bpm to 220 bpm.

· Filter stabilization of 1 sec is introduced to reduce fluctuations/ unnecessary frequency components.

Figure 2: Captured red image with intensity variation.
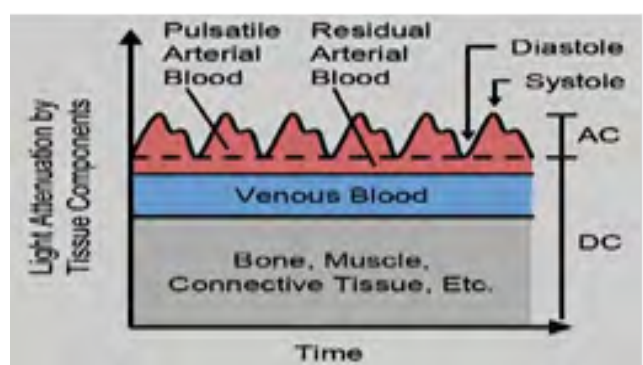

Figure 1: PPG capturing.

Figure 3: PPG light component.

· Assessment of pixel density if camera is pressed forcefully by fingertips.

· Leakage reduction by introducing Hann FFT window to remove DC if present at start up and no artificial high frequency when signal is treated by the FFT.

· Calculation is performed on all captured video frames after removing mistouch errors.

· Average duration of video considered 28-35 sec.

Algorithm

The algorithm is divided in two parts:

• Video processing and brightness signal obtaining.

• Signal processing, Filtering, Fft and Average Hr prediction.

Part A

Step 1: Capture contact unfocused RED image video of fingertip and capture video for at least 30 sec.

Step 2: Calculate Number of frames and fps.

Step 3: Count average pixel density/frame on RED plane (pixel variable).

Step 4: if pixel>=200 and pixel<=250 Keep it else ignore.

Step 5: set Fs as round (fps) (sampling frequency).

Part B

Step 1: Use 2nd order Butterworth band pass filter in the range of 40 bpm to 220 bpm to make signal lower and higher frequency noise free.

Step 2: Filter the signal with filter stabilization time=1 sec and initial signal cut-off period to 0.

Step 3: Set WINDOW_START=6 and WINDOW_END=12

For n=1 to fix((length(y)/(2*fs))-2) % y=filtered signal

Do

y2=y(n*fs:(n*fs+FFT_size-1));% 128 as FFT size.

window=hann(size(y2, 2))'; % Hann window.

Y2=abs(fft(y2.*window)); %FFT calculation.

Calculate single-sided positive frequency as f2.

YY=abs(Y2(WINDOW_START:WINDOW_END));

Find local maximum in IR spectrum as local_max_i

pk_i=6-1+local_max_i;

HR(n)=f2(pk_i)*60;

End

End

% Take average value of heart rate.

HR=sum (HEART_RATE (2:(length (HEART_RATE) -1)))/(length (HEART_RATE)-2);

AVG_Heart_Rate=round (HR).

Improvement Scope

We are currently working on performance analysis of this algorithm with more test data set in real world keeping in mind further improvement possibilities. We have noted below scopes that will be covered in our next papers with more real world test case analysis:

• Optimization analysis on upper limit of pixel density (to find a perfect range of brightness signal).

• Average optimum touches % calculation per video for calculating HR.

• Introduction of Machine Learning for analyzing touch pattern and thereby decision making.

• Correlation and Regression analysis.

• Experimental analysis on different smart phone videos.

• Factors affecting PPG while capturing video including heat by flash.

• Optimization analysis on other noises like motion (using white Gaussian Noise and Wavelet Analysis).

• Optimization analysis on HR calculation with different physical activities.

Testing

For maintaining originality, we have manually captured red image video of fingertips using mobile camera then used that raw *.mp4 file for analysis in MATLAB software. We have captured all videos in average voltage of light and at normal room temperature and at rest physical condition. Then the result is compared with two devices like Dr. Trust's Pulse Oximetry and portable wearable BP Machine by MEDISANA. For measuring heart rate, we have used below devices, software and hardware tools:

Smart Phone: Moto G Turbo Edition

Android: 6.0.1

Camera: Rear

Software: MATLAB Signal and Image Processing Toolbox.

Version: R2017b Hardware: Acer Laptop, Intel Celeron Processor.

Hardware: Acer Laptop, Intel Celeron Processor.

Platform: Windows 10.

We have taken below HR readings from Dr. Trust with 1 min interval in normal rest condition:

Left Fingertip: 77, 81, 80, 85, 82, 86, 75, 81, 80.

Right Fingertip: 83, 72, 73, 74, 81, 80, 79, 82, 83.

We have taken below HR readings from BP Machine by MEDISANA with 2 min interval in normal rest condition: 90, 86, 88, 86, 87, and 82. So the Average range lies in normal range 72-90 in 60 min. We have captured 5 videos from Moto G Turbo and analysed.
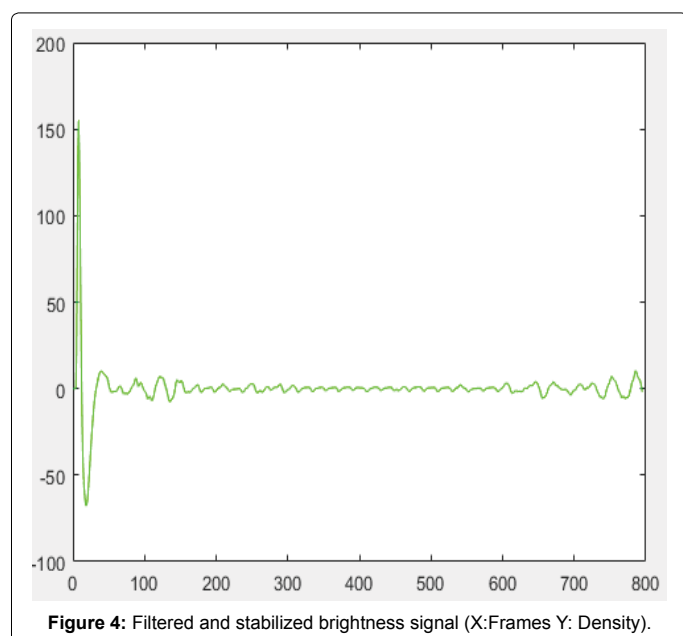
Miss touch average pixel density per frame in red plane is less than 200 (bad contact or more pressure on single area of fingertip) and more than 250 (more pressure and Non Red image → Yellowish Orange). In case of uniform more pressure, average pixel density/frame in Red plane>200 but sudden up and down in pixel density and thereby reflected in brightness signal.

File

Right hand, signal_1.mp4, fps=27, Touch error=4, frames=795, HR=82. With touch error, HR=81 so, algorithm works fine and touch error for only 4 frames at the beginning as Figure 4 and throughout the remaining signal train, brightness is consistent and in the range and no straight line in the signal. This is a perfect brightness signal with uniform pixel density (Figures 5-8).

File

Left hand, signal_2.mp4, fps=28, Touch Error=0, frames=962, HR=77. With touch error (=0), HR=77. Originality of the signal is not lost. So, algorithm is giving expected data if there is no touch error as well.
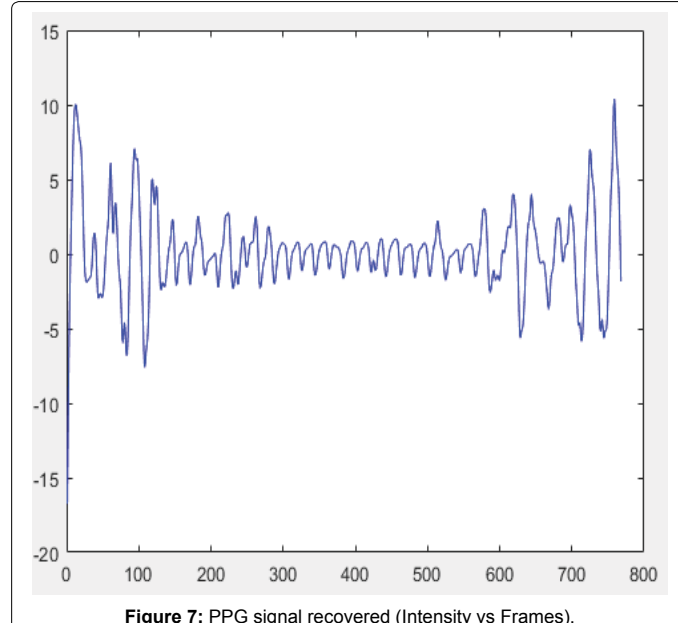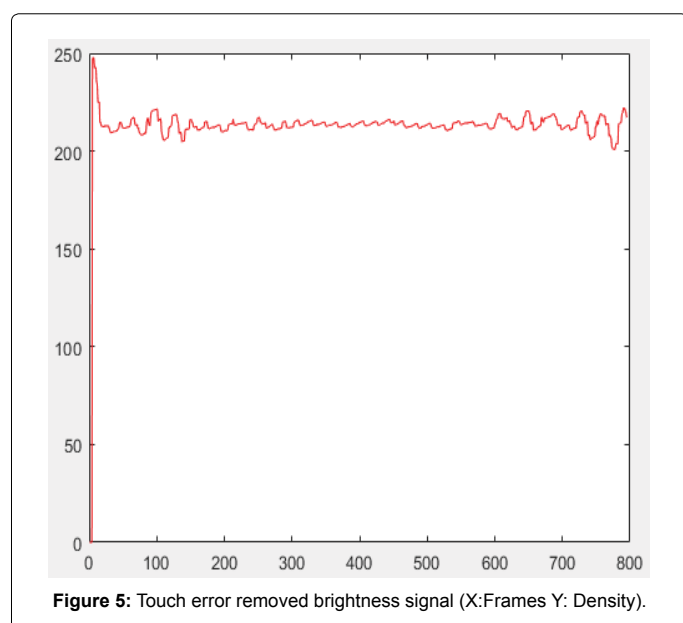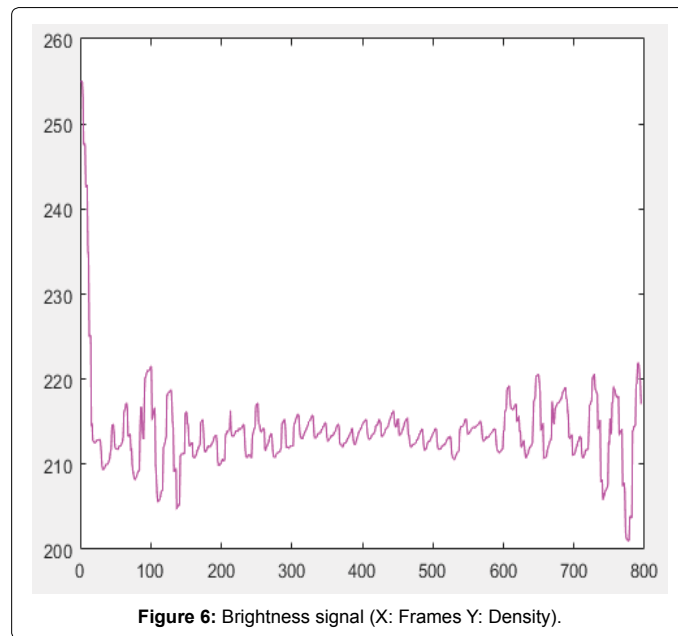
File

Left hand, signal_3.mp4, fps=28, Touch Error=86, frames=811, HR=77. With touch error, HR=80 (Unreliable). Yellowish orange image at the beginning (created flat line) and huge pixel density variation due to finger movement covering the camera so pixel density>200 but sudden up and down.

File

Right hand (intentionally miss touch is created), signal_4.mp4, fps=28, Touch Error=56, frames=770, HR=71. With touch error, HR=72 (Unreliable). It is because multiple touch error (<200 pixel density) in longer span and yellowish orange image at the beginning (created flat line). Limit % of miss touch error is under analysis for this category of signal with irregular waveform.
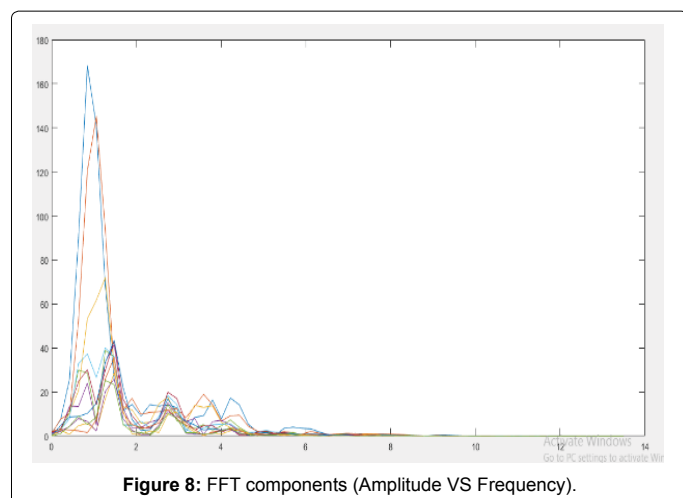

Figure 4: Filtered and stabilized brightness signal (X:Frames Y: Density).

Figure 6: Brightness signal (X: Frames Y: Density).

Figure 5: Touch error removed brightness signal (X:Frames Y: Density).

Figure 7: PPG signal recovered (Intensity vs Frames).

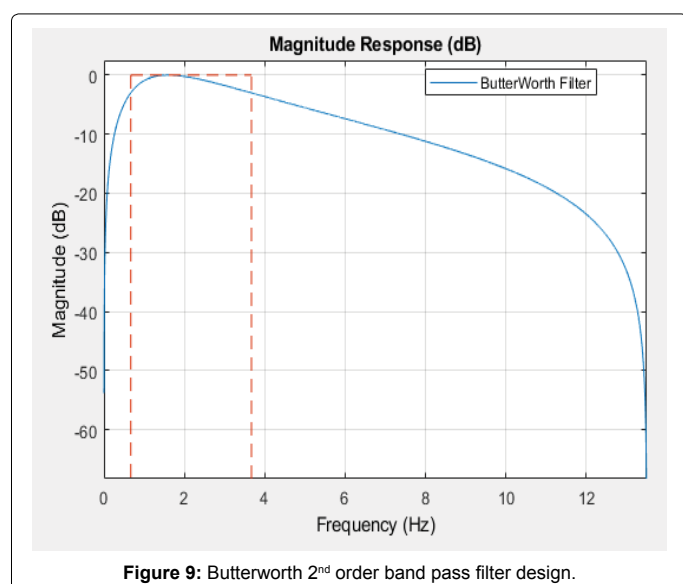**Figure 8:** FFT components (Amplitude VS Frequency).

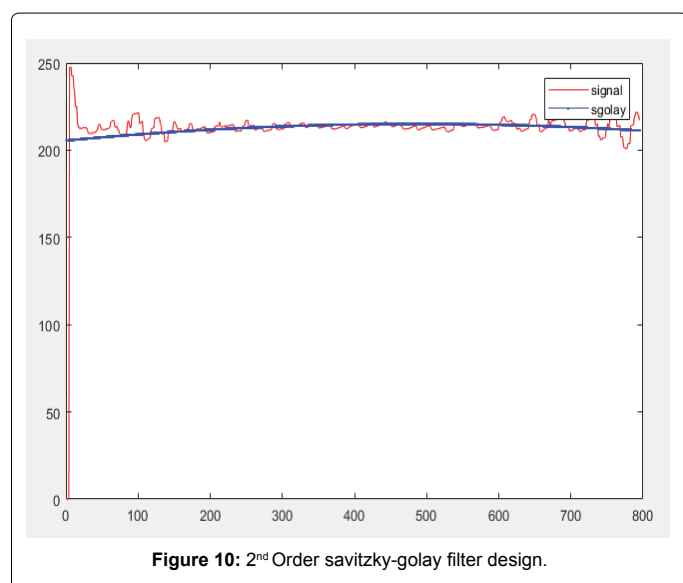**Figure 9:** Butterworth 2nd order band pass filter design.

Figure 10: 2nd Order savitzky-golay filter design.

File

Right hand, signal_5.mp4, fps=28, Touch Error=131, frames=815, HR=68. With touch error, HR=66 so our algorithm tries to recover signal from touch error. Non Red image Yellowish Orange, has produced flat brightness value at the beginning and bad touch at the middle.

A good PPG signal train can be obtained from pixel density in red plane/frame between 200-240 for most of the cases or sometimes little high and range 200-250. So, we have kept the range in between 200-250 and working on this for detail level analysis if any external factor is effecting its increment or not. In some cases, it has been observed that camera stabilization is taking 1-4 sec and in that time non red picture received which has pixel density>250 and flat line in brightness signal plot which we have removed for gaining original brightness signal.

Butterworth Vs Savitzky-Golay Filter

Butterworth filter tries to keep frequency response as flat as possible in its passband. It is an IIR filter. For low frequency signals, IIR filters are very good and it has fast processing power. The order of a filter means number of energy storage elements (Inductor/Capacitor) in the circuit. We have designed below band-pass filter of 2n order where n=1 to pass frequency band of PPG signal in the range of [0.66 3.3].

Savitzky-Golay Filter is an FIR filter used to filter frequencies outside the interest band and smooth the signal. FIR filters are always stable due to for a finite input, the output is always finite and it has property called linear phase. We have used 1st and 2nd order of Savitzky-Golay Filter on entire frame length of the captured video from where PPG signal is obtained.

Hd=designfilt('bandpassiir','FilterOrder',order,'HalfPowerFrequency1',(BPM_L/60),'HalfPowerFrequency2',(BPM_H/60),'SampleRate',fs); (Figure 9).

We have also checked if we can use it with Butterworth filter in the same algorithm-first use band pass filter for filtering noise and then use Savitzky-Golay Filter to smooth it and performed comparative study.

yf=sgolayfilt(y,order,framelen); %filter design. y is the input brightness signal and yf is the filtered signal. Framelen is taken as entire frame length of captured red video (Figures 10-12).
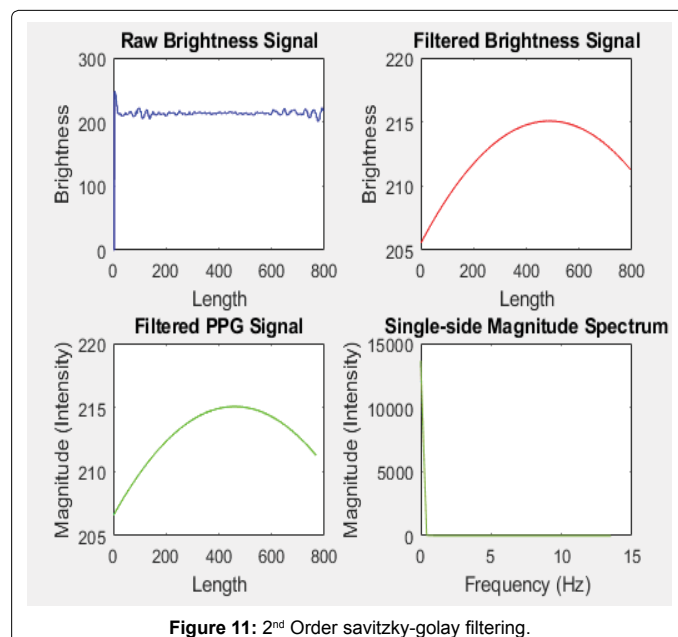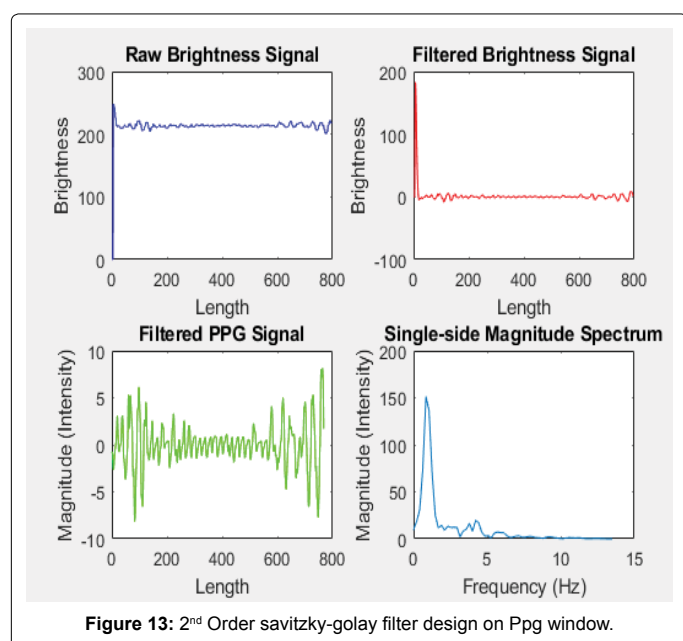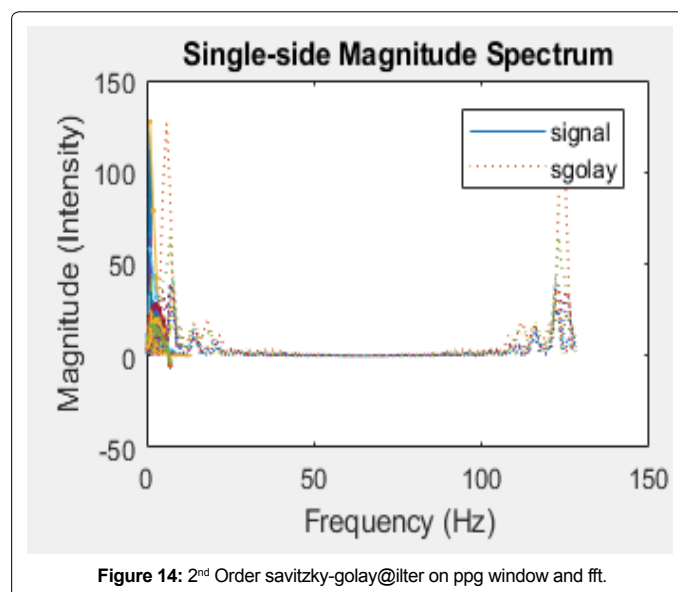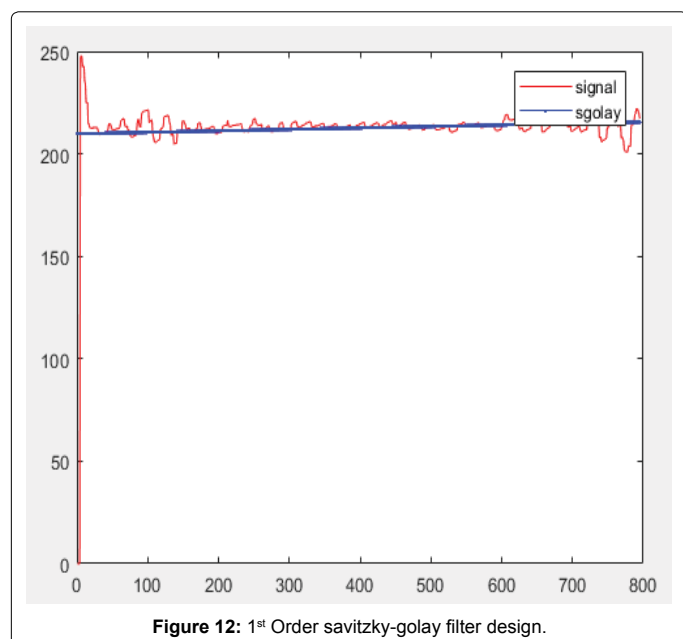

Figure 11: 2nd Order savitzky-golay filtering.

Figure 12: 1ˢᵗ Order savitzky-golay filter design.

Figure 14: 2ⁿᵈ Order savitzky-golay@ilter on ppg window and fft.

Conclusions

This study has opened up new challenges of PPG, digital signal, image processing and filtering where attention to be paid for more accuracy. All the observations mentioned here will be written down in next paper with detail level of mathematical and experimental study with more trial and signal property analysis with variation with factors. We are currently focusing on performance analysis of this algorithm with more test data set in real world keeping in mind further improvement possibilities with other heart parameter measurements which are important data sudden heart attack prediction. For the whole assessment, accurate data/noise free image/noise free signal or test data are highly required as it is very new area and related to health or personal safety.

Figure 13: 2ⁿᵈ Order savitzky-golay filter design on Ppg window.

Filtering the selected window from PPG to do smoothening along with band pass filtering with 2ⁿᵈ Order Butterworth.

IIR:yf=sgolayfilt(y(ppg(WINDOW_SECONDS1:WINDOW_SECONDS2)),order,(WINDOW_SECONDS2-WINDOW_SECONDS1)+1); %filter design (Figures 13 and 14).

Comparative Study

In this study we have run our algorithm with two different filter designs on signal_1.mp4 and signal_2.mp4 as discussed in this paper and compared the result.

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